

DYNACOMP

FLIGHT
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FLIGHT SIMULATOR

NORTH STAR

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MICROCOMPUTER FLIGHT SIMULATOR

VERSION 2.0

The following discussion describes the basic operation of the MICROCOMPUTER FLIGHT SIMULATOR which appeared in the book SIMULATION, Programming Techniques Volume 2, published by BYTE Publications, copyright 1979. In the section entitled "Simulation of Flight", the program is treated in great detail, including flow charts, derivation of the simulation equations, as well as considerable explanation of the characteristics by way of example. This document is meant to supply only the information required to actually exercise the simulation using console commands.

The first user response required is whether or not instructions are desired. As in most cases, the prompts are self-explanatory. Thus we will concentrate only on those inputs which may be a little confusing. The first set of inputs which require some explanation are the "flight characteristics" section. Here the user defines the basic operational properties of the aircraft via a set of parameters. The first is the plane mass in tons (English units). The second is the fuel load, also in tons. The third is the thrust fraction, which means the thrust (push/pull) as a fraction of the plane's mass. Thus a one ton plane having a thrust of .3 would have 600 pounds push/pull (eg., the propeller would exert a force of 600 pounds on the plane). The fourth parameter is the maximum plane speed in knots. This refers to the level (neither ascending or descending) flight speed under full throttle. The fifth parameter is the glide angle. This is the minimum angle of glide if the engine is off (thrust=0) and the flight speed is near stall. The angle is in degrees. The sixth input is the time increment in seconds. The relevance of the number is simple. If the take-off option is chosen, then this is the time step between commands. However, once in the air, as will be discussed shortly, the time increment can be changed whenever you are in the command mode.

A suggested set of flight characteristics parameters is:

- Plane mass- one ton
- Fuel mass- 0.3 tons
- Thrust fraction- .3
- Maximum speed- 180 knots
- Glide angle- 11 degrees
- Time increment- 3 seconds

One of two flight modes may be initially chosen; take-off and in-the-air flight. In the take-off mode, there are three requested inputs every command time increment. They are thrust, flaps and elevator angle. The thrust input must be between -1 and +1. This is the fraction of maximum power which is to be applied. A 1 means full power; a 0, no power. Note that the thrust can be reversed for braking. The flaps input refers to the desired flap angle, which must be between 0 and 45 degrees. Full flaps is 45 degrees. A high flap angle increases lift, reduces the stall speed and increases the drag. The third input, elevator angle, effectively changes the angle of attack and affects the lift and attitude. For example, if during level flight the elevator angle is increased, the nose of the plane will rise relative to the horizon, and the plane will begin to climb. The normal range of elevator control is -20 to +20 degrees. Remember, the plus direction tends to pull the nose of the plane up.

DO YOU WISH INSTRUCTIONS? (Y/N): ?H
 (Y/N): ?N
 DO YOU WISH TO FLY (TYPE F)
 OR TAKE-OFF (TYPE T):?F
 INPUT THE FOLLOWING PARAMETERS:
 MASS (TONS): ?1
 FUEL (TONS): ?.3
 THRUST FRACTION: ?.3
 MAXIMUM SPEED (KNOTS): ?180
 GLIDE ANGLE (DEGREES):?11
 TIME INCREMENT (SECONDS):?3

READY FOR FLIGHT

ALT.: 15832 FEET
 SPEED: 135 KNOTS
 STALL SPEED: 56 KNOTS
 ENGINE TEMP: 280 DEG
 FUEL 598 LBS.
 FLAPS: 0 DEGREES
 TRIM: -10 DEGREES
 THRUST: .3
 BANK: 0 DEGREES
 ATTACK ANGLE: 0 DEGREES
 HORIZON: 0 DEGREES
 HEADING OFF EAST: 45 DEG.
 LANDING GEAR: UP
 FLIGHT TIME: .05 MIN.
 CONTINUE?Y

CONTROL TOWER MESSAGE

 RANGE: 50 MILES
 CLIMB RATE: 0 FEET/SEC
 POSITION OFF RUNWAY: 135 DEG.
 WIND DIRECTION: 45 DEG.
 WIND SPEED: 0 KNOTS
 CONTINUE?Y

COCKPIT CONTROLS

COCKPIT CONTROL LETTER:?T
 CONTROL VALUE:?0

COCKPIT CONTROL LETTER:?E
 CONTROL VALUE:?-4

COCKPIT CONTROL LETTER:?C

ALT.: 15834 FEET
 SPEED: 124 KNOTS
 STALL SPEED: 62 KNOTS
 ENGINE TEMP: 170 DEG
 FUEL 598 LBS.
 FLAPS: 0 DEGREES
 TRIM: -10 DEGREES
 THRUST: 0
 BANK: 0 DEGREES
 ATTACK ANGLE: -3 DEGREES
 HORIZON: -3.3 DEGREES
 HEADING OFF EAST: 45 DEG.
 LANDING GEAR: UP
 FLIGHT TIME: .1 MIN.
 CONTINUE?Y

- This is another example in which the instructions option was not chosen. Observe the input error check and re-try.
- The "flight" option is chosen.
- This is the parameter input which is referred to elsewhere in the documentation.
- The thrust fraction terminology may cause some confusion. As used here, it represents the the maximum engine "pull". During the flight it refers to the portion of this power which is to be applied.
- Below the stall speed, lift rapidly decreases. If the engine overheats, it will shut down.
- This parameter can be set by the pilot. Some experimentation will be required to arrive at a value which allows neutral flight.
- Perhaps the most important variable.
- Direction of the plane's flight path.
- Range is relative to the west end of the runway.
- Again relative to that end of the runway.
- Relative to east.
- Speed is rounded to nearest knot.
- The general sequence is a control letter followed by a control value, except for the "C" (continue) control.
- An illegal control letter will be accepted, but no action will be taken. However, a control value will also be required for bookkeeping.
- Note the changes in the flight conditions due to the 3 second time interval.
- The changes shown are extreme as the engine was shut down while traveling relatively fast. Rapid deceleration is apparent.

The examples shown were obtained by running the North Star version of the MICROCOMPUTER FLIGHT SIMULATOR. The TRS-80 display is very similar. The PET 2001-8, being limited in memory size, required alterations which resulted in removal of the instructions option, as well as a few non-essential features. Otherwise, the simulation is very similar to the full North Star version.

THERE ARE TWO POSSIBLE INITIAL FLIGHT CONDITIONS; ONE WITH PLANE 50 MILES FROM THE AIRPORT AT AN ALTITUDE OF SEVEN MILES, AND THE OTHER WITH THE PLANE ON THE RUNWAY. THE USER SUPPLIES THE FOLLOWING CONSTANTS:

- *MASS OF THE PLANE
- *THRUST AS A FRACTION OF THE PLANE WEIGHT
- *MAX. LEVEL FLIGHT SPEED
- *GLIDE ANGLE AT STALL
- *ELEVATOR COEF. (NOSE)
- *TIME INCREMENT

THERE ARE TWO MESSAGE SETS. ONE IS A COCKPIT DISPLAY WHICH IS SELF-EXPLANATORY. THE OTHER IS A CONTROL TOWER MESSAGE GIVING RANGE, DESCENT RATE AND POSITION RELATIVE TO THE RUNWAY. THE FLIGHT CONTROL FUNCTIONS ARE:

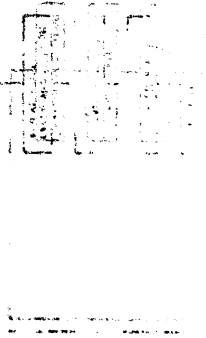
- C=CONTINUE WITH SAME
- T=FRACTION OF MAX THRUST
- B=BANK ANGLE IN DEGREES
- E=ELEVATOR (DEGREES)
- F=FLAPS (0 TO 45 DEG.)
- R=TRIM (DEGREES)
- G=LANDING GEAR (0 UP/1 DN)
- S=NEW TIME INCREMENT

IT IS SUGGESTED THAT THE TAKE-OFF OPTION BE FIRST CHOSEN FOR EXPERIENCE. A GOOD STARTING TIME INCREMENT IS THREE SECONDS. A PRACTICAL SET OF PARAMETERS FOR A SMALL PLANE MIGHT BE: WEIGHT, ONE TON; FUEL, 0.3 TONS; THRUST, 0.3; MAXIMUM SPEED, 180 KNOTS; GLIDE ANGLE, 11 DEGREES.

GOOD LUCK

Notes which are included in the unabridged versions of the MICROCOMPUTER FLIGHT SIMULATOR.

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Simulation of Flight

F.R. Ruckdeschel

Several years ago, at a trade show in the New York City Coliseum, I saw a demonstration that simulated the flight of an airplane between two pylons. The simulation employed a cartoon-like representation of the pilot's cockpit view on a large video screen. The pilot interaction was via a joystick. When given a chance to test my own skill, I crashed.

The demonstration was impressive, particularly because it was in real time and attempted to mimic the flight of an actual flying machine. The major time cruncher in that animation was probably the display update. Today's microcomputer is capable of analogous system simulations.

The simulation presented here treats the flight characteristics of the model airplane using aerodynamic equations. For display purposes the model assumes zero visibility flight conditions in which the cockpit window view is replaced with an instrument panel readout and control tower communications. This type of interaction is much more technical than the simple graphics display, and perhaps more realistic. To further enhance the realism, many standard cockpit controls have been simulated, including elevator, rudder, ailerons, flaps and throttle. These controls were individually defined and then combined into an overall flight model. The flight characteristics simulated involve several inertial and aerodynamic effects, including

momentum, centrifugal force, air pressure, lift, drag and stall. The user chooses the basic flight characteristics which are used to represent an airplane design, ranging anywhere from a glider or Piper Cub to a jumbo jet or Phantom.

One objective of the flight simulation is to bring the plane down from a cruise altitude, 50 miles from an airport, to land on a two mile long runway (which can be shortened, if desired). The simulation portrays the landing itself, including deceleration once on the runway. Another objective is to take off from the same runway.

The extensive list of model features may best be understood by actually running the simulation or by reading through the mathematical and aerodynamical descriptions. Most users will initially have trouble flying the plane, and it may take some time to learn how to land it (probably after many crashes). The difficulty was created intentionally; flying a real airplane is not simple.

The simulation is considered in the context of a system model that contains various subsystems and environments, and whose output is the flight trajectory. The subsystems are the flight controls and displays. The three environments considered are takeoff, landing and flying. These three environments are linked through the executive. Transition from one to another is controlled automatically.

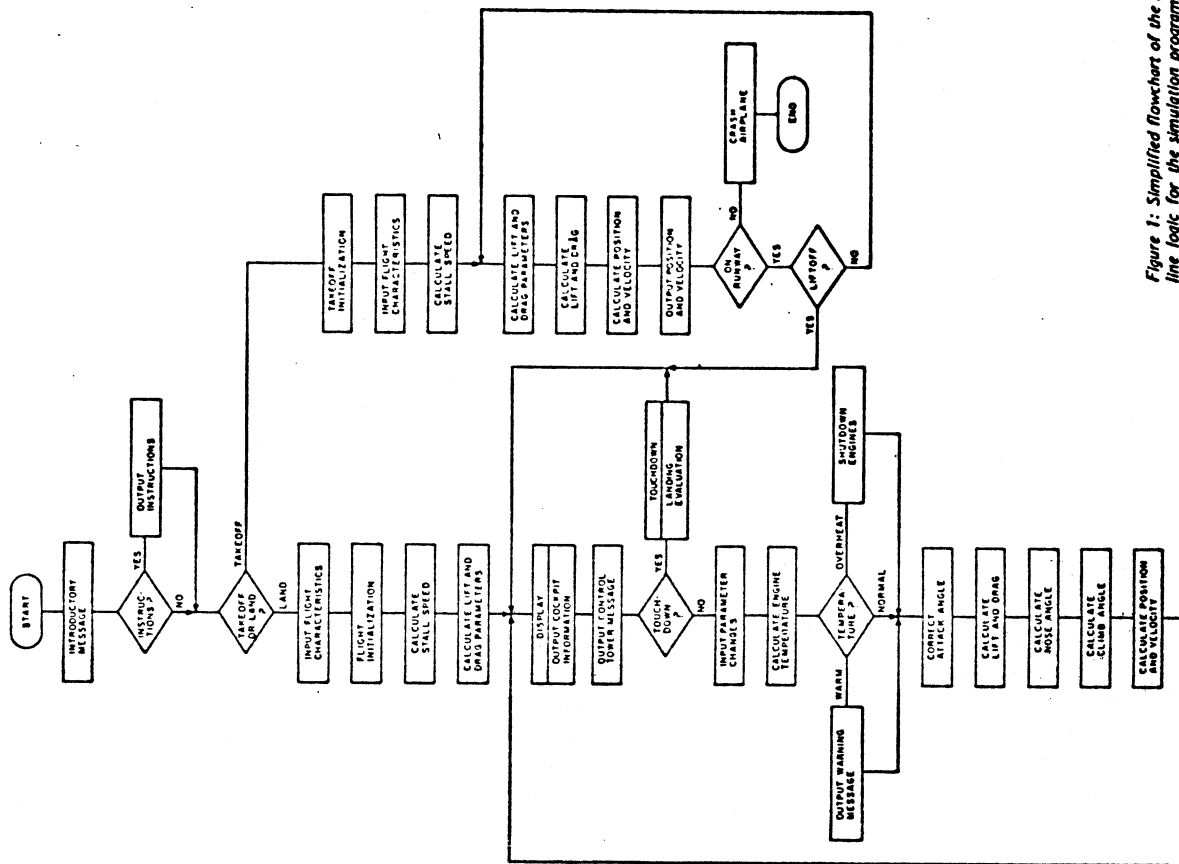


Figure 1: Simplified flowchart of the main-line logic for the simulation program. The three submodules (DISPLAY, TOUCHDOWN, and RUNWAY) are shown in figures 2 through 4.

The change along (trajectory) is given by:

$$\Delta \vec{r} = \left(\frac{\Delta x}{\Delta t} \right) \left(\frac{\Delta t}{M} \right) \left(\frac{\Delta t}{M} \right) \Delta t \quad (15)$$

The change in the climb angle is a vector which is instantaneously perpendicular to the velocity vector. For simplicity we will assume the related velocity change to have only a vertical component scaled by the cosine of the climb angle:

$$\Delta \vec{v} = \vec{v} \cos(\theta) \frac{d\theta}{dt} \Delta t = \cos(\theta) \left\{ \frac{T}{Mv} \sin(\theta) - \frac{g \cos(\theta)}{v} + \frac{L}{Mv} \right\} \Delta t \quad (16)$$

The third velocity change contribution is from the change in heading which is assumed to be only in the horizontal plane. Thus:

$$\Delta \vec{v} = \left\{ \frac{\vec{v} \times \vec{v}}{v^2} \right\} \frac{d\theta}{dt} \Delta t = \frac{L \sin(\theta)}{v \cos(\theta)} \left\{ \vec{v}_x - \vec{v}_y \right\} \Delta t \quad (17)$$

The notation $\vec{v} \times \vec{v}$ stands for the vector cross product. This is used as an approximation.

Combining the above equations we have:

$$\Delta \vec{v} = \frac{\Delta t}{Mv} \left[\left\{ T \cos(\theta) - Mg \sin(\theta) - D \right\} \vec{v}_x - \frac{L \sin(\theta)}{\cos(\theta)} \vec{v}_y \right] \quad (18a)$$

$$\Delta \vec{v} = \frac{\Delta t}{Mv} \left[\left\{ T \cos(\theta) - Mg \sin(\theta) - D \right\} \vec{v}_x + \frac{L \sin(\theta)}{\cos(\theta)} \vec{v}_y \right] \quad (18b)$$

$$\Delta \vec{v} = \frac{\Delta t}{Mv} \left[\left\{ T \cos(\theta) - Mg \sin(\theta) - D \right\} \vec{v}_x + v \cos(\theta) \left\{ T \sin(\theta) - Mg \cos(\theta) + L \right\} \right] \quad (18c)$$

Equation (18c) can be replaced by the more obvious equation:

$$\vec{v}_x = v \sin(\theta)$$

Equations (18) are used in conjunction with equations (13) and (14) to give the updated velocity and position of the airplane. The constitutive equations are:

$$\begin{aligned} L &= \text{lift} & (\text{equation 1}) \\ D &= \text{drag} & (\text{equation 2}) \\ \alpha &= \text{attack angle} & (\text{equation 9}) \\ \theta &= \text{climb angle} & (\text{equation 11}) \end{aligned}$$

Now that most of the theory of operation of the simulation has been covered, consider listing 1 which is the actual program being used.

The Program

Initial Conditions

The user designs an aircraft through the choice of a few simple initial flight values. The number of input parameters has been kept to a minimum by using approximate aerodynamic interrelations within the program. The parameter values suggested in the program text correspond to a small propeller driven plane carrying about four hours of fuel when at 80% throttle (thrust). Varying the following parameters will result in many interesting designs:

- Weight of Plane: Self-explanatory.
- Fuel: At the outset of the simulation the pilot inputs the fuel load in the same units as the mass of the airplane. The fuel usage during flight versus the throttle setting is assumed to be parabolic; full throttle eats up fuel rapidly. The constants were chosen such that under normal conditions, full throttle can be maintained for one to two hours before the fuel runs out. However, the engine will overheat long before that occurs.

One aerodynamic effect of fuel consumption is that the airplane weight changes with time. This is reflected in the airplane going out of trim.

- Thrust Fraction: This is the maximum force which can be exerted by the engine relative to the unladen airplane weight. Generally, a higher thrust fraction results in faster response to controls and the ability to climb rapidly. The engine power is derated exponentially with altitude, as is the lift. Thus, there is a built in ceiling (maximum level flight altitude) for all designs. If a space shuttle is to be simulated, the restriction on engine power P1 must be removed in line 1450 of listing 1.
- Maximum Speed and Glide Angle: These are key input design parameters which strongly determine the flight characteristics of the aircraft. The stall speed increases with increasing maximum speed. Stall speed is also an increasing function of glide angle. Planes with high maximum thrust ratios (maximum thrust versus plane weight) also tend to have relatively low stall speeds. These design parameters also affect the lift and drag coefficients in nonobvious ways. Experimentation is required to create

The take off option also leads to an initialization routine within the program. In this case all controls except trim are generally set to their zero positions. The trim is set to -10°. The airplane is parked at the beginning of the runway with the engine temperature set to 300°F.

Take Off Controls

There are only three controls exercised during take off: thrust, flaps, and elevators.

- Thrust: In the user initialization of the program, a value for the maximum thrust (jet push; propeller pull) in terms of a fraction of the airplane's weight is specified. This cannot be subsequently changed during a run. The engine control which does exist is that which determines how much of this potential thrust is applied over the next time period. This fraction is represented by T. Its maximum absolute value is unity, but it may be positive or negative. If positive, the plane accelerates; if negative, it decelerates and possibly rolls backwards. A reversible pitch propeller would permit this latter type of behavior.

For an average airplane, a reasonable take off value for the thrust is generally 0.8 to 1.0. Note, however, that maintaining a thrust value of 1.0 will eventually lead to overheating of the engine. A thrust of 0.8 can be sustained indefinitely.

- Flaps: The effect of flaps is to increase the lift of the plane at a given speed. In doing so, the drag is also increased. The flaps may be set to between 0° and 45° with the maximum lift occurring at 45°. If an attempt is made to lower the flaps further, they will simply peg at the full flaps (45°) limit. Under normal take off conditions, half flaps (22.5°) is usually used from the beginning of the roll. For some aircraft design choices, the use of full flaps during the take off roll may result in so much drag that the required flight speed may not be reached by the end of the runway. The quickest take off sequence is achieved by employing zero flaps at the beginning of the roll and full flaps when the required air speed is attained. However, control of the plane as it leaves the ground then becomes tricky; the plane may sharply climb, decelerate, stall (drastically lose lift), and crash.

- Elevator Angle: The net effect of the elevator control is to raise or lower the nose of the airplane relative to its trajectory. When rolling on the ground, the elevator control causes the nose to point up or down relative to the horizon. The airplane's response to the controls is speed-dependent. If the airplane is stationary, the elevator control has no effect.

Internal Initializations

There are parameter initializations which occur within the program after the flight or take off option is chosen. When the flight option is chosen, the airplane's position is set to fifty miles from the airport with an associated altitude of seven miles. This can be changed by altering the values of X1, X2, and X3 on line 980 of listing 1. The initial speed is chosen to be three quarters maximum and the velocity vector is directed southeast. The velocity vector is described by the component values S1, S2, and S3; the speed (V) equals $\sqrt{S1^2 + S2^2 + S3^2}$. In this initialization case S3 (the vertical velocity component) is set equal to zero and S1 is equal to S2.

There are several other parameters which are automatically specified:

- Flaps are positioned up (F1=0)
- Angle of attack is zero (A1=0)
- Throttle is at 30% of maximum (T=30 X maximum thrust)
- Bank angle set to zero (B=0)
- Engine temperature set to 280°F (T9=280)
- Trim angle is 0° (R9=0)
- Landing gear is up.

The net result of these initial conditions for the flight option is that the pilot takes over control of an airplane which is momentarily in level flight. The craft will most likely tend to climb or descend unless the control settings are changed. Thus, it is advisable to choose a small time increment when initially taking over the controls. Once the flight is stabilized, longer time increments may be used. The controls themselves are discussed later.

on the time increment chosen and the operator response time.

Alrborne Displays and Controls

Once the airplane is off the runway, the control messages change into two groups: cockpit display and control tower messages. These two sets of information allow the pilot to attempt level flight, turn the airplane around, and land it back on the runway.

Cockpit Display

There are fourteen flight parameters shown in the cockpit display. Some are simple reminders of control settings, while others record the aerodynamic response to these controls.

- **Altitude:** The airplane's altitude is given in feet. This is generally more than sufficient resolution to take off and flying. However, during the last stage of the approach for landing this increment is often not fine enough. In such a situation, the angle of descent and, more importantly, angle of attack and horizon angle are used.
- **Speed:** This display indicates air speed. The ground speed is not displayed and is affected by the wind. It will be observed that nosing up will usually lead to a decrease in air speed and nosing down will cause the reverse to occur. Thrust significantly affects speed.

Very high speeds can be attained in a dive. At 20% above the airplane design maximum a warning message is issued. At 40% above the maximum a wing failure abruptly occurs.

- **Stall Speed:** The stall speed is based on program computations using the design parameters chosen by the user at the beginning of the simulation. However, *accelerated stall* can occur in tight banks (turns). This is simulated in the program by making the stall speed an increasing function of the bank angle.

- **Engine Temperature:** This displays the engine temperature in degrees Fahrenheit. Temperatures below 430°F are considered safe. Between 430°F and 450°F, a warning is issued. Above 450°F the engine shuts down until it cools off. Turn on is not automatic; a thrust value (T) must be given to restart the engine. The engine temperature is calculated from the thrust used over several previous time periods. This may take a while before the engine can be restarted. Needless to say, glide conditions exist in the interim.

- **Fuel:** The remaining weight of fuel is displayed in 1 pound increments. The rate of consumption depends on the square

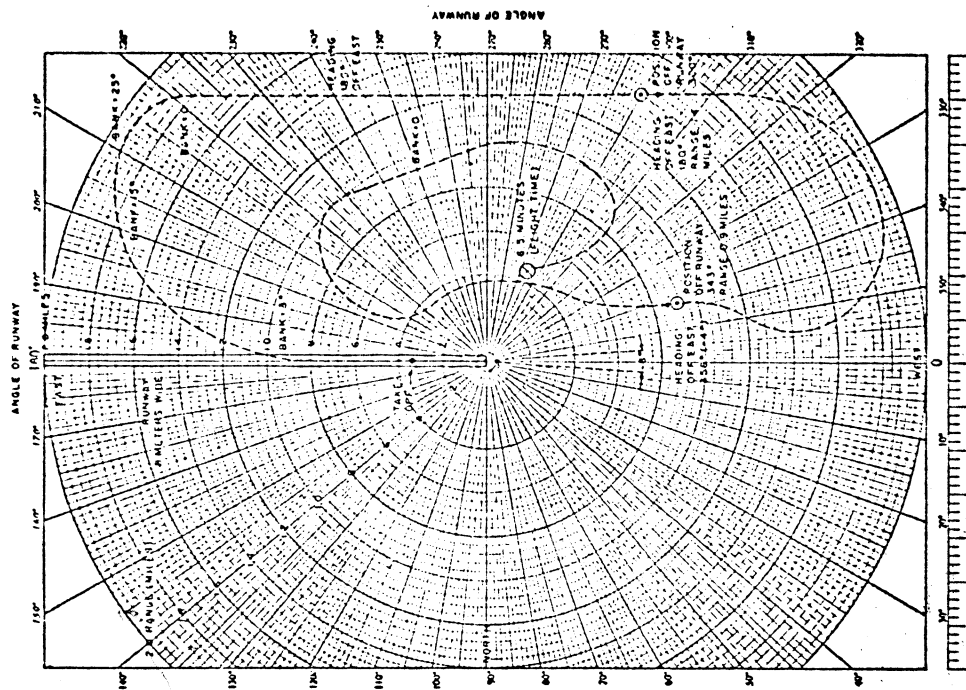


Figure 8: Polar coordinate representation of an actual computer simulation in which the course was not plotted and carefully navigated during the flight. Subsequently, the printout was used to reconstruct the flight. Toward the west end of the runway the angular position off the runway changes rapidly, leading to confusion unless the course is continuously followed on a polar coordinate paper. The coordinates and headings associated with two particular positions are shown as examples. The location convention is not difficult, but may initially be somewhat confusing to those not familiar with polar coordinate geometry.

of the throttle (thrust) setting. Fuel consumption thus tends to be greatest during take off and climbs. The effect of fuel consumption on the overall plane weight is included.

- Flaps, Trim, Thrust, Bank: Readouts of control settings given by the pilot.

- Attack Angle: This generally corresponds in sign to the elevator angle. The magnitude of the response is speed dependent. A special condition exists when a critical angle of about 16° is exceeded. The attack angle pegs at that value. Unless in a dangerous landing approach situation, the attack angle (when flying upright) should be between roughly -3° and $+5^\circ$. When flying inverted (yes, the simulation can handle that case also), the angle of attack should be strongly negative, say -8° or more. Observe that when flying upside down, the bank, flap, trim, and elevator controls are reversed in their flight path effects (unless you are thinking invertedly also).

- Horizon: This display gives the angle of the horizon as it would be seen from the cockpit window. It is affected by both the climb angle and the angle of attack (a linear addition). It is an important display during final approach and landing. If the horizon is lower than -6° upon touchdown, the nose gear collapses and the plane crashes. Between -6° and 0° a nose rebound occurs, bounding the plane back into the air with the nose pointed up at an angle negatively proportional to its prior horizon. Unless care is exercised in applying the controls at this point, the plane will repeatedly bounce, nose dive, or stall. A negative horizon on touchdown causes a lot of trouble.

- Heading Off East: This display indicates the instantaneous direction of travel of the craft relative to due east. This particular convention was chosen as the runway runs from west (start) to east (end). When making a final approach for landing, the heading should be near 0° (between roughly 356° , -4° , and 4° in order to hit the runway properly).

- Landing Gear, Flight Time: These are simply status displays.

Control Tower Message

It is assumed that a radar tracking control tower exists which can aid in instrument flying by giving range, speed, and meteorological information. The following information is transmitted to the pilot:

- Range: This is the radial distance in miles from the west end of the runway as illustrated in figure 8. This is a key positional display.

- Climb and Descent Rate: This is the vertical speed of the plane in increments of one foot per second. It is an important flight indicator which is particularly useful in evaluating the net response to the elevator and throttle controls. Close to touchdown, however, the resolution of this display falls short of ideal. In this case the air speed, angle of attack, and horizon indicators become the main readouts.

- Position Off Runway: This readout complements the range display. It gives the angle of the plane relative to the beginning of the runway as shown in figure 8. For example, when the airplane is on or over the runway headed due East, the angle off runway is 180° . The coordinate orientation has been chosen such that the angular position upon final approach should be near 0° or 180° depending on the approach. Also, the heading off east should be near 180° or 0° , respectively (with no wind). Quantitatively, if the heading is 180° off east at a range of 400 meters (about one quarter mile), the angular position should be between 359.4° (-0.6°) and $+0.6^\circ$. This is not easy to do while also maintaining a good glide angle. Fortunately the runway is long.

- Wind, Direction, and Speed: The existence of a changeable wind sometimes makes landing a difficult chore. It largely affects the heading one must take in order to maintain an appropriate glide path. If the cross runway component of the wind exceeds six knots, the airplane may run off the side of the narrow runway if the heading just compensates for the wind at touchdown. Two alternatives exist: circling until the wind changes direction or diminishes, or changing heading just before touchdown to straighten out the airplane relative to the runway. Since the bank angle control works under the assumption of no slip, side slip is not simulated. If it were it could be used to handle the crosswind.

Cockpit Controls

There are quite a few controls which are exercised by the pilot during flight. Two, the time increment (S) and the continue character (C), have to do with the mechanics of the simulation. Once a control parameter is entered, it is latched until changed by the pilot. This is convenient once a quasi-stable flight pattern has been established. However, establishing a stable flight path is not easy. Constant control conditions may cause the airplane to rise, lose air speed and lift, nose over, dive, pick up air speed and lift and rise again. This cyclic pattern may be very extreme under some conditions.

Cockpit Controls

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The flight controls available in the cockpit are as follows:

- Throttle (Thrust) (T): This is the fraction of maximum thrust available, the maximum having been established in the program initialization. The entered value should be between zero and one for positive thrust, or a negative one and zero for negative thrust.

- Bank Angle (B): This puts the airplane into a no slip bank (centrifugal force perpendicular to wings). A value of 180° will invert the craft; 360° will complete the roll. Absolute values greater than 300° are not allowed. Vertical lift is lost during a bank according to the cosine of the bank angle. Stall speed also increases as the turn becomes tighter. During a tight turn, the airplane will generally lose altitude even though the nose may be on the horizon. In such a situation, increased throttle and raising the nose above the horizon helps.

- Elevators (Attack Angle) (L): As mentioned earlier, this affects the angle of the airplane's wings relative to its trajectory (ie: the attack angle). The response is speed dependent. If an attempt is made to exceed an absolute attack angle of 16° , a significant loss in lift results due to turbulence in the air flow over the wings. In effect, a stall occurs. Attack angles over 10° should be avoided.

As noted earlier, the attack angle response to the elevator control is air speed dependent. In a dive, as the air speed increases, so does the attack angle response, thus increasing lift and reducing the dive. In a climb, as the air speed decreases, the reverse happens. Thus there is some self-compensation built into the control.

- Flaps (F): Explained earlier. Once in flight, the flaps should be set to 0° to reduce drag.

- Trim (R): As far as the program is concerned, trim has an effect proportional to flaps: positive trim increases lift and negative trim decreases lift. In flight, the trim is adjusted to somewhere between -10° to $+10^\circ$ to give neutral elevator controls (ie: E set to zero gives level flight) at the chosen cruise speed and altitude. As fuel is consumed the craft will tend to rise; "trimming" will counter this. Many pilots enjoy continuously trimming their craft; it replaces nail biting.

The trim value set by the initialization is -10° . During take off this can not be altered. Once in the air the trim angle may be set to zero. However, the change should be made slowly to maintain control over the plane. Rapid changes lead to over control and erratic flight.

- Landing Gear (G): An input value

for G of one lowers the landing gear. Setting G to zero raises the gear. The simulated airplane has an automatic warning system which acts when the airplane is descending and is below an altitude of approximately one hundred feet. After a long flight it is not unusual to forget to lower the landing gear. This should be checked perhaps a quarter mile from touchdown so that there is time for compensation for landing gear (aerodynamic) drag.

Touchdown Conditions

Landing on the runway is a very exacting exercise since several criteria must be satisfied.

First, the landing gear must be down. Next, the airplane must be within four meters of the runway centerline. Though the runway is long, it is also narrow. The airplane must obviously also be on the runway (not short or long). The horizon should be greater than -6° ; 0° is very good.

The quality of the touchdown is finally determined by the rate of descent at contact. If less than 1.6 ft/s, the landing is considered soft. If between 1.6 and 5 ft/s, the landing is rated moderate. Between 5 and 33 ft/s touchdown is declared hard and a bounce occurs. Beyond that a crash condition exists.

One of the dangers to be wary of after a bounce is subsequently nosing over into the runway. To avoid this keep the nose up and apply a little more throttle.

Once the craft has settled on the runway and deceleration has begun, a test is made to determine if the end of the runway has been reached. If so, a crash has occurred; there are no survivors if the speed on leaving the runway was greater than 20 knots.

Deceleration is simple: reverse thrust is applied by inputting a negative throttle value. If forward thrust is used instead, the program will switch to the take off routine.

Additional Surprises

In addition to these initializations and commands there are several more variables which affect the airplane's simulated performance:

- Wind Effects: The effect of wind on the airplane velocity relative to ground is modelled using a random number generator. On the average, once every ten seconds the wind direction and magnitude randomly shifts (actually, there is some correlation with the previous wind vector). The net effect is that the wind vector slowly shifts with time. This effect is most important

when trying to land. In fact, under some conditions, landing may be impossible.

- Ice Storms: There is one chance in a hundred that in any particular time period an ice storm will develop. The consequence of such an occurrence is an increase in the airplane's weight by 50% due to ice on the wings. This obviously creates a problem if altitude can not be maintained at a safe throttle level and if the runway is too far away.

- Altitude: The effect of altitude on lift, drag, and engine thrust is accounted for by assuming that the air density decreases exponentially with altitude (decreases by 1/e approximately every 23000 feet). This automatically places a flight ceiling restriction on the particular simulation; it is not possible to escape the Earth. This feature is not an actual subroutine, but is part of other subroutines.

Command Structure

The pilot input command structure is simple. In the flight environment the computer supplies command prompts (?) and expects replies as follows:

```
? <command letter> <carriage return>
? <control value> <carriage return>
```

When on the runway, inputs for the throttle, flaps, and elevators are specifically asked for.

Program Execution

It is common to see someone spend more than an hour attempting to learn how to fly (just fly; not land) the simulated airplane. The simulation is not easy to master, like many Lunar Lander type programs. Practice is required to get the feel of the flight response of the particular airplane design chosen. In addition, the response changes with altitude due to the change in air density. I have seen some sessions last more than six hours (computer time, not flight time), eventually ending in a crash. The longest flights tend to be those in which the flying option is chosen.

This has initial conditions in which the airplane is flying at seven miles altitude 50 miles from the runway, heading in the wrong direction. The pilot must learn to navigate somewhat to make a proper landing. Beginners usually discover quickly that it is not very difficult to accidentally stall or, if the thrust is great enough, to loop the airplane. A tendency to loop is particularly apparent for high lift or high thrust airplane designs. Recall the balsa wood (or styrofoam) gliders of your youth; when the main wing was moved forward, the airplane had a tendency to loop and stall in a cyclic fashion. A similar situation is possible under certain conditions in this simulation.

The simulation is sufficiently complete to allow not only flying loops, but also rolling and flying upside down (if the angle of attack is sufficiently negative), and perform the aerobatics normally associated with flying.

A very simple simulation run is shown in listing 2. The take off option was chosen, with the intent being to immediately land after take off using the remaining runway, and then take off again. The flight path takes one through many flight regimes, including lift off, free flight, touchdown, and runway maneuvers.

Notes

The computer simulation presented has not been completely debugged even though it has been extensively exercised. A problem with large simulations is that a bug may go undetected for some time. To aid in fixing such problems and upgrading the simulation submodels, a variables list is given in table 1.

Although the physical description of the aerodynamics of flight is not rigorous in all its subelements, the model approximations are sufficient to simulate the general interactive characteristics of flying. This philosophy of subsystem approximation for the sake of system simulation is key to the successful modeling of many systems. Quite often it is too easy to get bogged down in the details of modeling the elements only to find that the important system features may be demonstrated using less than precise inputs. This flight simulator is one such example.

Program Notes

The simulation was encoded using a subset of North Star BASIC, Version 6 Release 2. I tried to avoid using special functions which may not be available in less advanced BASIC interpreters so that the program could be easily translated into most BASICS. The statement line widths were generally kept below 40 characters because of the printout limitations of my SWTPC PR40 matrix printer.

There are a few peculiarities of North Star BASIC which must be observed in making a translation to another BASIC.

Line Delimiters: In MITS BASIC, two or more statements can be placed on one line if they are separated by a colon. North Star BASIC uses a backslash. When listing the program using Processor Technology's VDM-1 system this results in a NEW SPEED request. The VDM-1 driver can easily be changed (see manual) so that some less troublesome character prompts a display speed change.

Strings: All strings in North Star BASIC are one dimensional and, if greater than ten characters in length, must be subscripted. This is not necessary in MITS BASIC; lines 20 through 50 may be deleted and replaced with:

```
20 DIM K(12).
```

Format: In North Star BASIC, the carriage return after a print statement can be avoided by using a comma. In MITS BASIC, a semicolon is used.

The basic operators used are fairly standard: +, -, /, *, <, =, >, and !. The functions called are SIN, COS, SORT, EXP, ABS and INT. The commands employed are IF-THEN, GOTO, GOSUB, RETURN, INPUT, PRINT, STOP, and REM. These capabilities are common to most BASIC interpreters. Observe that two functions are conspicuously missing: LOG and ATAN. The logarithm function is not used and the inverse tangent function is calculated in a subroutine since several BASICS, including North Star's, do not have this function.

Running the program in the form shown in listing 1 requires about 14 K bytes of program memory. Removal of all REM statements, the instruction subroutine, and the instruction string list reduces the memory requirement to about 8 K bytes. A further memory savings can be incurred if an ATAN function is used along with the commands IF-THEN-ELSE, and ON-GOTO.

Program execution is relatively fast. The majority of the time is spent printing out conditions and awaiting pilot input. The longest pause associated with actual computing (based on an IMSAI 8080 with fast memory) is less than 7 seconds. Although the program looks long and inefficient in BASIC, little would be gained by going to machine language or a compiler unless graphics were to be included. Graphical displays require very rapid updating routines and necessitate the use of machine language routines. A small part of the inefficiency apparent in the program is due to its user-oriented structure. All internal calculations are performed in metric units, while all IO routines use the traditional units such as knots and feet. ■

[illegible]

Table 1: This table of variables and parameter definitions will aid in updating the simulation in listing 1.

B = bank angle (radians)
B9 = random number in wind effects routine
C1 = friction drag coefficient
C2 = induced drag coefficient
C3 = lift coefficient
C9 = random number in wind effects routine
D = drag (Newtons)
D3 = climb angle (radians)
F = total flap, including trim (normalized; $45^\circ = 1$)
F1 = flaps
F9 = fuel supply (kilograms)
G = gravitational constant (meters/second²)
K11 = landing gear index (0 or 1)
K12 = thrust sequence
L = lift (Newtons)
L1 = constant in ATAN routine
L2 = constant in ATAN routine
L3 = constant in ATAN routine
L4 = small constant very near zero
M = total airplane mass (kilograms)
M1 = dummy variable passed to ATAN
M2 = dummy variable passed to ATAN
M9 = initial plane (normalized) mass (kilograms)
N1 = maximum thrust ratio (normalized)
N3 = fraction of available power used (normalized)
P1 = air density (normalized)
P2 = feet to meter conversion factor
P3 = feet to meter conversion factor
P4 = degrees to radian conversion factor
P5 = meters to mile conversion factor
P6 = (meters/second) to knot conversion factor
Q1 = elevator control (radians)
R = range of plane from runway (meters)
R2 = length of runway left (feet)
R9 = trim (radians)
S1 = eastward speed component (meters/second)
S2 = northward speed component (meters/second)
S3 = vertical speed component (meters/second)
S4 = eastward wind component (meters/second)
S5 = northward wind component (meters/second)
T1 = attack angle (radians)
T2 = glide angle (radians)
T3 = time increment (seconds)
T4 = accumulated time (seconds)
T7 = dummy variable
T9 = engine temperature ($^\circ\text{F}$)
U2 = angle (radians)
V = line of flight speed (meters/second)
V1 = maximum sea level speed (meters/second)
V2 = stall speed
W = dummy variable
X = dummy variable in ATAN routine
X1 = east coordinate (meters)
X2 = north coordinate (meters)
X3 = altitude (meters)
Y = dummy variable
Y1 = dummy input variable
Z = dummy variable

```

*****
AFS: 725
ELEVATOR DECREASES: 78
*****
HORIZON: 27
WAY SPEED: 66 KNOTS
ALL SPEED: 53 KNOTS
FT (S): 116
875 FEET OF RUNWAY LEFT
LOST TIME: 15 SECONDS
*****

```

ATTACK ANGLE: 3 DEGREES
HORIZON: 0
RUNWAY SPEED: 53 KNOTS
STALL SPEED: 53 KNOTS
FLIGHT TIME: .65 MIN

CONTROL TOWER MESSAGE
RANGE: 55 MILES
CLIMB RATE: 22 FEET/SEC
POSITION OF RUNWAY: 190 DEG
WIND DIRECTION: 0 DEG
WIND SPEED: 0 KNOTS

TOUCHDOWN

TOUCHDOWN MEDIUM

RUNWAY SPEED: 58 KNOTS
7624 FEET OF RUNWAY LEFT
THRUST: 71
ELEVATOR DEGREES: 70
RUNWAY SPEED: 43 KNOTS
7402 FEET OF RUNWAY LEFT
THRUST: 70
ELEVATOR DEGREES: 70
LIFT (S): 3
7216 FEET OF RUNWAY LEFT
THRUST: 71
LIFT (S): 0
7032 FEET OF RUNWAY LEFT
THRUST: 71
ELEVATOR DEGREES: 70

HORIZON: 0
RUNWAY SPEED: 25 KNOTS
STALL SPEED: 53 KNOTS
LIFT (S): 0
6800 FEET OF RUNWAY LEFT
FLIGHT TIME: .72 SECONDS

THRUST: 71
ELEVATOR DEGREES: 70

HORIZON: 0
RUNWAY SPEED: 42 KNOTS
STALL SPEED: 53 KNOTS
LIFT (S): 0
6600 FEET OF RUNWAY LEFT
FLIGHT TIME: .45 SECONDS

THRUST: 71
ENGINE

FLAPS: 775
ELEVATOR DEGREES: 70

HORIZON: 0
RUNWAY SPEED: 53 KNOTS
STALL SPEED: 53 KNOTS
LIFT (S): 0
6548 FEET OF RUNWAY LEFT
FLIGHT TIME: .45 SECONDS

THRUST: 71
ENGINE

FLAPS: 775
ELEVATOR DEGREES: 70

HORIZON: 0
RUNWAY SPEED: 53 KNOTS
STALL SPEED: 53 KNOTS
LIFT (S): 0
6240 FEET OF RUNWAY LEFT
FLIGHT TIME: .51 SECONDS

THRUST: 71
ENGINE

FLAPS: 775
ELEVATOR DEGREES: 70

HORIZON: 2.0
RUNWAY SPEED: 68 KNOTS
STALL SPEED: 53 KNOTS
LIFT (S): 121
5702 FEET OF RUNWAY LEFT
FLIGHT TIME: .44 SECONDS

YOU ARE IN THE AIR

ALT: 1000 FEET
SPEED: 68 KNOTS
STALL SPEED: 53 KNOTS
ENGINE TEMP: 445 DEG
FUEL 580 LBS
TIME: .5 SECONDS
THRUST: 1
BANK: 0 DEGREES
ATTACK ANGLE: 2.0 DEGREES
HORIZON: 0
RUNWAY SPEED: 42 KNOTS
STALL SPEED: 53 KNOTS
FLIGHT TIME: .95 MIN

CONTROL TOWER MESSAGE
RANGE: 86 MILES
CLIMB RATE: 22 FEET/SEC
POSITION OF RUNWAY: 190 DEG
WIND DIRECTION: 0 DEG
WIND SPEED: 0 KNOTS
